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A NOVEL APPROACH TO IMPROVE WEDM PERFORMANCE ON INCONEL718, BY USING SMALL DIAMETER ZINC COATED WIRE

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ABSTRACT

In this paper, a novel approach to increase the wire electrical discharge machining performance by using small diameter wire is presented. As wire in wire electrical discharge machining (WEDM) is the only externally added into the intrinsic system, its role is determinant in the performance of WEDM. It is characterised by essential mechanical, electrical, and thermal properties. Here 0.15, 0.20, and 0.25 mm diameter zinc coated wire is used, on 8, 10 and 12 mm thick rectangular blocks of Inconel718, to investigate the performance measures such as the material removal rate (MRR), and surface roughness (SR). Taguchi L27 orthogonal array is employed to ascertain the effect of varying diameter. It is observed that MRR and SR. are greatly influenced by wire diameter. A small size wire diameter is proved to be better on all accounts, promising a high MRR with lower SR. Further SEM studies revealed that the alterations such as debris and oxide deposition seen on the surface are very less and is acceptable with no foreign particle accumulation on the surface revealed by EDAX. There are no cracks developed in the cutting with small diameter wire.

***KEYWORDS:** WEDM, MRR, SR & Kerf Width*

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Original Article

1. INTRODUCTION

Wire electrical discharge machining is a sophisticated alternative to conventional machining, with absolutely no mechanical forces, rotating parts, quite a silent operation with reasonable cutting speed. It is disruptive machining in which material is removed from the workpiece by discontinuous sparks generated from the continuously fed wire at a predetermined interval, of predetermined intensity, which is used to erode the material in discrete quantity thermally (Tosun et al., 2004). The dielectric used has the added function to cool and carry the molten pool of metal and debris. It has evolved from basic die sinking machines, but now it surpasses the parent machine to the extent that die sinking can be thought of by-product of wire EDM(Patil & Brahmankar, 2010). WEDM has extended applications in almost all fields ranging from conductive to nonconductive ceramics (Maher et al., 2015)from miniature medical instruments to substantial aircraft propulsion parts (Pilligrin et al., 2018) and WEDM has disseminating process in the manufacturing sector for the last 3-5 decades since its inception. Nickel-based alloys are considered to be stable(Sharma et al., 2018)and abundantly used in elevated heat applications like propulsion turbine ((Klocke et al., 2016), (Welling, 2014)space shuttles, and nuclear reactors (Li et al., 2013). However, alloys pose difficulty in machining with conventional machines due to self-hardening behaviour and the generation of the tremendous amount of heat leading to tool breakage (Wang et al., 2017). WEDM being contactless proved to be one of choice in these alloys. WEDM can be

considered as a set of smaller subsystems (Mahapatra & Patnaik, 2006), (Han et al., 2007). The power system (electrical), flushing systems (hydraulic), wire and table movement system (mechanical) are all working independently and adjusted independent of each other. Hence there is scope for improvement and expertise, as the machine itself cannot decide, although the manufactures give the guideline for selected materials for rough, trim, and finish cutting. The hydraulic system provides minimal scope for improvements as the pumps fitted of standard quality. However the mechanical system allows adjusting the tension, feed within the desired range, but machine table movement is CNC controlled and hardly any error reported in that over the years(Yan et al., 2016). So only remains scope for improvements in the electrical subsystem. The electric system is inherent to the machine and heart of the machine as the machine runs on electricity. As one can easily adjust current, voltage, pulse on, and pulse off, within the range provided. But selecting the proper combination of all the electrical parameters for different workpiece characteristics is still a challenging task (Aggarwal et al., 2015) and there is a lot of research is reported to find the optimum setting of these control parameters to get the maximum material removal rate and minimum surface roughness. In this regard, the researchers have made various attempts to improve the performance of WEDM in machining of nickel alloys.(Rao, 2010) reported peak current as the most significant factor influencing MRR and SR. Pulse on time reported as the significant factor for these performance measures in similar research by (Ramakrishnan & Karunamoorthy, 2006). While machining high Armor steel using WEDM, it is reported that in addition to pulse on, pulse off time, servo voltage as the thrust variable (Bobbili et al., 2013). It is reported that high SR obtained is the ultimate result of large wire diameter generating greater kerf width accompanying greater distortion of material and wire breakage (Cabanes et al., 2008) during machining when the wire gets broken. Further, the use of rethreaded wire caused a considerable increase in roughness because of discontinuity and the time taken to replace wire is, in fact, the reason for low MRR. Wire diameter is the deciding factor for, higher SR, high cost, highest in accuracy and high wire lag. Hence it is imperative to study wire behaviour in detail by targeting wire as the main entity, and few researchers endorsed this(Dauw et al., 1989), (Tosun & Cogun, 2003), (Puri & Bhattacharyya, 2003). Reported literature includes the contribution of (Gamage & DeSilva, 2016). They used an experimental based approach to monitor a 0.2 mm diameter brass wire breakage. Two video cameras were deployed for time study recorded 5 seconds for automatic pneumatic rethreading, whereas manual rethreading takes about 5.24 minutes. They determined the total time and energy lost due to wire failure. The machine operators normally amend the machining parameters such as wire feed a wire advance and sparking frequency to avoid further wire failures. However, this slows down the process further adversely affecting energy consumption. The time is taken to resume machining after each wire failure is non-productive as all subunits are running and consuming power until the operator rethreads the wire. (Pramanik & Basak, 2016) probed into the degradation of the wire electrode, by altering the pulse on time and wire tension to divulge the interaction between affecting parameters. In this study, it is explored that the electric sparks not only remove the workpiece material but also affect the dimensions of the electrode. The original circular shape became oval regardless of the workpiece material type indicating permanent deformation of the wire due to high temperature and possible interaction with electrolyte and molten workpiece material. It is suggested that the two types of wire movements causing wire vibration, the cutting speed at which wire moves into the workpiece and the wire speed at which the wire moves from top to bottom and wire tension applied. (Antar et al., 2011) studied the material effect of the wire electrode in WEDM performance. The comparison of coated wire over non-coated one has been made in respect of productivity, workpiece surface, surface roughness and surface integrity. Increase in productivity of 40 % was recorded with coated wire, under the same operating conditions. (Nourbakhsh et al., 2013)compared high-speed brass wire with zinc-coated wire. It is observed that the Zinc-coated wire gives higher cutting speed and smoother surface finish. However, the uncoated wire produced more cracks, craters, and

melted drops as compared to coated brass wire. (Chalisgaonkar & Kumar, 2014) exploited microstructure analysis of the work surface explained that the zinc coated wire produced the overlapping thick layer of debris while uncoated wire developed the craters under similar operating conditions. (Ishfaq et al., 2018) presented the WEDM of cladded steel to optimise the cutting performance. The influence of workpiece orientation has been studied along with wire diameter. An increase in cutting speed has been reported when the diameter decreases from 0.30 to 0.20 mm. (Sharma et al., 2016) studied the effect of brass wire diameter on the surface integrity. For the comparative investigation of different diameter wires low, medium and high discharge energy setting was selected. It was observed that with smaller diameter wire the cutting speed is 20 % higher compared to the larger diameter wire under similar experimental conditions, the surface roughness of larger diameter wire was found 8 % higher. The smaller diameter wire cuts the delicate specimen easily. However, with lower wire diameter wire breakage is the main hurdle. This research with varying diameter was confined with plain brass wire only.

Therefore literature shows a clear margin in research related to wire related parameters particularly cutting with small diameter zinc coated wire. Zinc coated wire is widely accepted for its better performance as seen from the literature. So in this paper, proven zinc coated wire of 0.15, 0.20 and 0.25 mm was explicitly manufactured to study the repercussion of using small diameter wire compared to a large diameter under the similar operating conditions. Hence the primary objective of this research is to determine the effect of using small diameter wire for improving the MRR and surface finish and additionally, the effect of job thickness is explored.

2. MATERIALS AND METHODS

2.1. Workpiece and Wire Material

A peculiar profile cutting of Inconel718, blocks of (25 x 25) mm of varying thickness 8, 10 and 12 mm is carried out in this research. The chemical composition of Inconel718 and zinc coated wire electrode was performed in a reputed lab by using spectroscopy is as given in Table 1. The specifically manufactured zinc coated brass wire and wire guides of 0.15, 0.20, and 0.25 mm diameter were used. Electronica make Eco cut is employed to carry out this research.

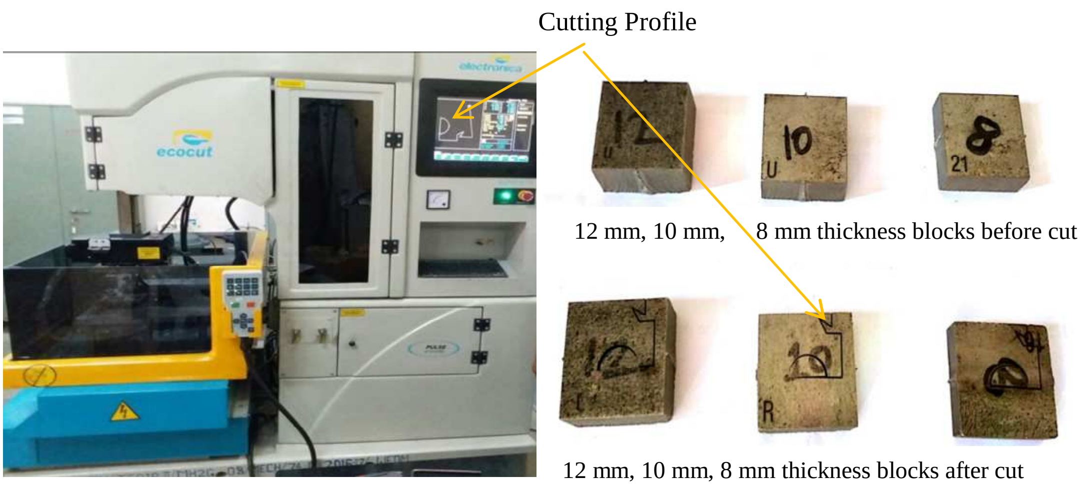


Figure 1: Machine Tool and Inconel Blocks

Table 1: Chemical Composition of Inconel718 and Zinc Coated wire

Workpiece Material Inconel718										Electrode Wire	
Element	**Ni**	**Fe**	**Cr**	**Nb**	**Mo**	**Ti**	**Co**	**Si**	**Mn**	**C**	**Cu**	**Zn**
Weight %	54.132	19.6	16.5	5.13	3.14	0.89	0.26	0.2	0.11	0.038	59.92	39.96

Five process parameters namely Wire diameter, Pulse on time (Ton), Pulse off time (Toff), Wire feed (Wf) and work material thickness were selected as input variables during peculiar profile cutting of Inconel718. Four two way interactions of Wire Diameter × Pulse on, Wire Diameter × pulse off, Wire Diameter × wire feed and Wire Diameter × work material thickness was selected Table 2. The experiments were performed in entirely random order, and each experiment was repeated twice to reduce the experimental error.

Table 2: Process Parameters and their Setting

Process Parameter (Unit)	Level-1	Level-2	Level-3	Fixed Parameters	M/c Unit
Wire Diameter (mm)	0.15	0.20	0.25	Peak Current(Ip)	12
Pulse on time (µs)	114	117	120	Servo Voltage	45
Pulse off time (µS)	58	55	52	Servo Feed	2100
Wire Feed (m/min)	6	8	10	Wire Tension	4
Work Material thickness (mm)	8	10	12	Dielectric Pressure	1

2.2. Measurement of Performance Indicators

The machining outcomes namely, the material removal rate, surface roughness, kerf width were assessed for this experimental investigation are given in Table 3.

Material Removal Rate is determined by using (1)

MRR. = Wb-Wa/ ρ × t mm3/ min (1)

Where

Wb= Weight before machining in grams measured

Wa= Weight after machining in grams

ρ = Density of Inconel – 718 in grams/mm^3

t = Time taken for machining in minutes, recorded by digital stopwatch

Surface Roughness (SR): Mitutoyo's surface roughness tester was used for the direct reading of roughness average (Ra).

Table 3: Experimental Results for the Performance Measures

Expt Run	Wd mm	Ton µs	Toff µs	Wf m/min	Wmt Mm	MRR 1 mm3/min	MRR 2 mm3/ min	SR 1 µm	SR2 µm
1	0.15	114	58	6	8	1.445	1.491	1.966	1.957
2	0.15	114	55	8	10	1.567	1.682	2.328	2.514
3	0.15	114	52	10	12	1.798	1.840	2.175	2.107
4	0.15	117	58	8	12	1.591	1.742	2.118	2.025
5	0.15	117	55	10	8	1.949	1.890	2.429	2.438
6	0.15	117	52	6	10	2.300	2.206	2.418	2.397
7	0.15	120	58	10	10	1.949	2.114	2.374	2.266
8	0.15	120	55	6	12	2.249	2.368	2.118	2.025
9	0.15	120	52	8	8	2.764	2.789	2.791	2.999
10	0.2	114	58	6	8	2.173	2.257	2.089	2.037
11	0.2	114	55	8	10	2.448	2.690	2.124	2.246
12	0.2	114	52	10	12	2.821	2.863	2.382	2.366
13	0.2	117	58	8	12	2.539	2.438	2.248	2.169
14	0.2	117	55	10	8	3.121	3.222	2.882	2.658
15	0.2	117	52	6	10	3.511	3.627	2.37	2.57

Table 3: Contd.,

16	0.2	120	58	10	10	3.136	3.426	2.738	2.938
17	0.2	120	55	6	12	3.490	3.381	2.547	2.525
18	0.2	120	52	8	8	4.429	4.404	2.999	3.06
19	0.25	114	58	6	8	2.041	2.103	2.157	2.127
20	0.25	114	55	8	10	2.927	2.859	2.284	2.434
21	0.25	114	52	10	12	4.226	4.243	2.466	2.364
22	0.25	117	58	8	12	2.421	2.432	2.459	2.317
23	0.25	117	55	10	8	2.945	2.917	2.554	2.494
24	0.25	117	52	6	10	3.417	3.470	2.836	2.728
25	0.25	120	58	10	10	3.040	3.002	2.826	2.659
26	0.25	120	55	6	12	3.131	3.126	2.537	2.323
27	0.25	120	52	8	8	3.903	3.822	3.628	3.606

Wd : Wire Diameter, **Ton** : Pulse on time, **Toff** : Pulse off time, **Wf** : Wire Feed,
Wmt : work material thickness,
MRR : Material removal rate, **SR** :Surface roughness, Experimental Run #18: Highest MRR, Experimental Run #1: Lowest SR

3. RESULTS AND DISCUSSIONS

3.1. Main Effect Plots

Taguchi's analysis for the mean value of response variables was carried out and is correlated with input parameters. The main effects plots figure 2, showing the effect of control parameters for the material removal rate, surface roughness graphically. The higher, the better strategy is used for MRR while smaller the better is used for surface roughness.

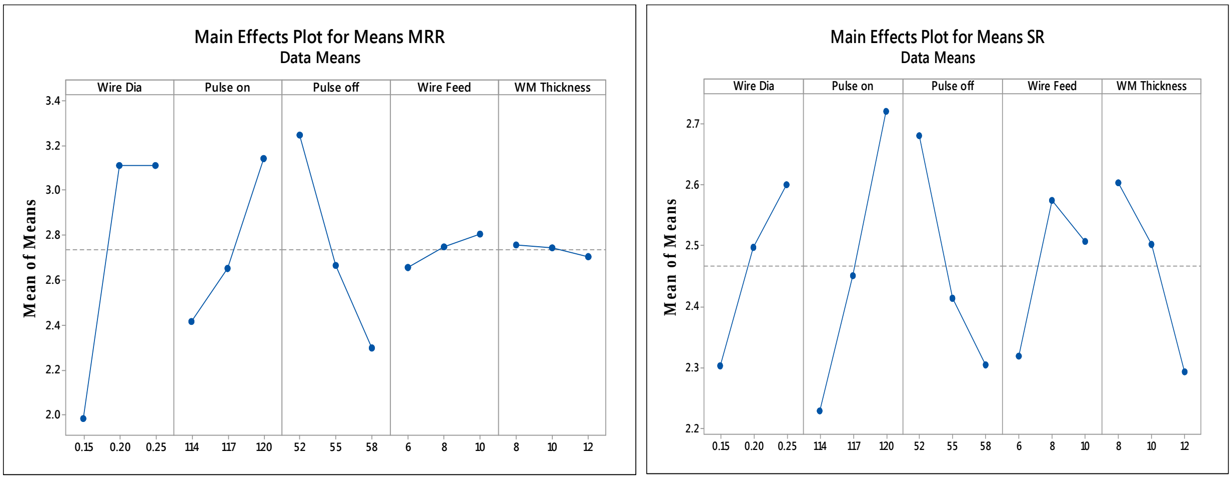


Figure 2: Main Effects Plots for MRR and SR

From the main effects plot of MRR, it is observed that with an increase in pulse on time (Mahapatra & Patnaik, 2006) the MRR increases. The highest MRR of 4.429 mm3/minis obtained with 0.20 mm small wire diameter. As the relative wire transport speed is comparatively higher with same effective feed (Ishfaq et al., 2018) increases the removal of debris. The movement of small wire diameter inside workpiece is rapid as compared to large wire diameter because of its smaller volume. Large wire diameter means more surface to be vaporised, and hence more time, reducing wire feed in the workpiece, and resulting in reduced MRR. In the case of surface roughness as the pulse on time increases the energy supplied per spark increases leading to larger craters and hence the higher value of surface roughness (Shandilya et al., 2011). This follows for wire diameter, as wire diameter increases surface roughness also increases. The best surface

roughness of 1.957 µm is obtained with 0.15 mm wire.

3.2. Anova

Analysis of variance is a statistically based, objective decision-making tool for detecting any differences in the response that might be attributed to the variation in the control parameters considered in the study are given in Table 4.

Table 4: ANOVA of MRR and SR at 95 % Confidence Level

ANOVA of Material Removal Rate (MRR)					ANOVA of Surface Roughness		
Factor	**DF**	**F-Value**	**P-Value**	**% Contribution**	**F-value**	**P-Value**	**% Contribution**
Wire Diameter	2	1314.00	0.000	49.98 %	53.59	0.000	12.97 %
Pulse on time	2	424.90	0.000	16.16 %	141.92	0.000	34.36 %
Pulse off time	2	712.87	0.000	27.11 %	88.36	0.000	21.39 %
Wire feed	2	17.99	0.000	0.68 %	41.52	0.000	10.05 %
WM thickness	2	2.35	0.114	0.08 %	59.14	0.000	14.32 %
Wire Dia ×Pulse on	4	57.56	0.000	2.18 %	8.46	0.000	2.04 %
Wire Dia ×Pulse off	4	41.32	0.000	1.57 %	8.67	0.000	2.09 %
Wire Dia ×Wire Feed	4	28.80	0.000	1.09 %	9.76	0.000	2.36 %
Wire Dia ×WM thickness	4	29.03	0.000	1.10 %	1.56	0.213	0.37 %
Error	27						
Total	53						

MRR Model Summery	S 0.0760827	R-sq 99.52%	R-sq(adj) 99.05%	R-sq(pred) 98.07%	SR Model Summery	S 0.113160	R-sq 97.03%	R-sq(adj) 94.17 %	R-sq(pred) 88.13 %

Wire diameter is the most significant and influencing parameter for MRR with a percentage contribution of almost 50 %. This might be due to the small diameter wire that encounters less resistance to penetrate material as compared to the large diameter wire. From metallurgical theory to destroy the intermolecular grain boundaries, a small wire diameter will act as a sharp edge tool, as compared with higher diameter will serve as a blunt tool. So less resistance will be offered by a material to the small wire diameter as compared to the large wire diameter. Its action is analogous as a sharp blade as compared with the knife. Wire diameter is the third most influencing and important parameter for surface roughness as can be seen from the ANOVA Table4. Pulse on time is observed to be the most dominant process parameter for deciding the surface roughness. This might be due to cross-sectional area exposed to heat is increased as wire diameter increased resulting in more volumetric debris and craters and melted deposits. More distortion of the work material will take place if it cuts with a large size knife. Better MRR and SR with small diameter is obtained, and this is in line with the previous research(Sharma et al., 2016).

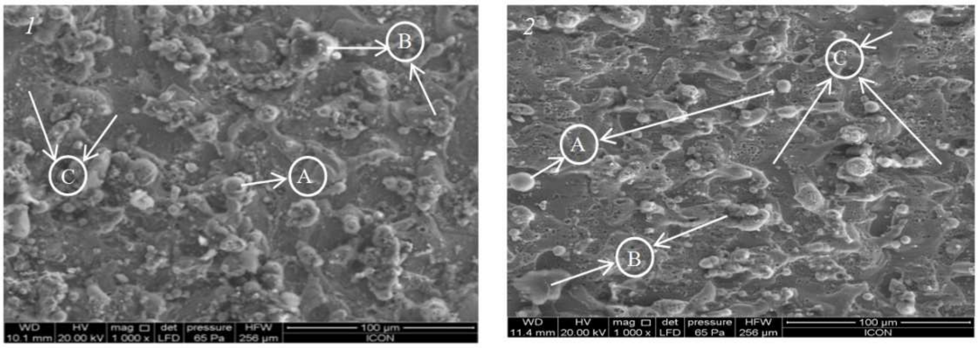
3.3. Surface Topography Analysis

FEI make Quanta 200 with EDS attachment SEM was used for microscopic examination of the workpiece cut with WEDM. The samples were examined at 1000X magnification figure 3. The prime purpose of the analysis was to study the microstructure obtained by a small wire diameter to affirm regular cutting as would be done by large wire diameter. Experimental parametric levels are tabulated above the graph in figures.

Micrograph 1 is obtained from the experimental run #18, giving the highest material removal rate of 4.429 mm^3/min and a roughness value of 2.99 µm. In this case, significant MRR is obtained with 8 mm thick block of Inconel718, considered to be the one of the hardest and challenging to cut material with the use of small wire diameter of 0.20 mm. There are no visible micro holes and cracks hence a stable cutting with small wire diameter of 0.20mm.

Experiment Run 18, High MRR = 4.429, SR =2.999				
0.200	120	52	8	8
Wire Diameter	Pulse On	Pulse Off	Wire Feed	Block Thickness

Experiment Run 1, low MRR = 1.445, low SR = 1.957				
0.150	114	58	6	8
Wire Diameter	Pulse On	Pulse Off	Wire Feed	Block Thickness



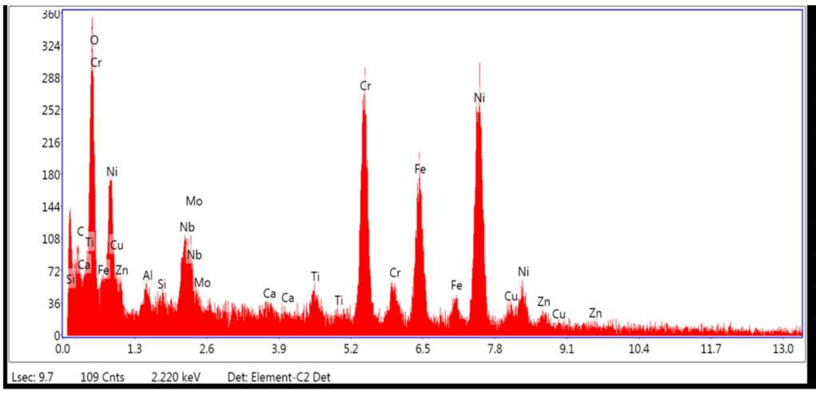
A: Oxides, B: Debris, C: Base material

Figure 3: SEM Topography for High MRR, Low MRR, Low SR

From the micrograph 2, there is less number of debris deposited while the more base material is visible. The lowest MRR is obtained due to the lowest setting of machining parameters. However, there is an increased percentage of oxides. Though the MRR is small being smaller diameter wire there are no craters formed both on the workpiece as well as wire tool. Also, the zinc coating on wire evaporates(Nourbakhsh et al., 2013) faster as compared to brass wire and hence a lowest surface roughness of 1.957 µm is obtained.

3.4. EDX Analysis

Energy dispersive x-ray analysis is used for determining the composition of material figure 4. It is useful in identifying contaminants as well to quantify their proportions on the boundary of the specimen. It is an inherent arrangement with a scanning electron microscope. The graph and excel sheet obtained from EDX is showing vacant electron excited by the energy received from the available composition. The higher a peak in a spectrum, more amount of material is available in the specimen.



Element	Weight %
C	6.82
o	9.34
Si	1.12
Nb	2.91
Mo	1.79
Ti	1.80
Cr	15.98
Fe	15.30
Ni	34.84
Cu	4.68
Zn	4.45

Figure 4: EDX Graph for Experimental Run #18

From the EDX of experimental run 18 giving highest MRR, peaks of Chromium, Nickel and Iron are visible. Worth to be noted is smaller concentrations of zinc 4.45 %, and copper 4.68 % which is from the zinc coated wire used for the experimentation. The carbon percentage is increased whereas the nickel percentage is decreased. Very less concentration of other unwanted materials is seen from the EDX spectrum and hence cutting with small wire is feasible and does not produce any unwanted effects.

4. CONCLUSIONS

There is a remarkable improvement in the MRR, SR with small wire diameter.

- It is observed that the small wire of 0.20 mm diameter gives highest MRR of (4.429) mm^3/min under the stable and equal operating range.
- For surface roughness small wire of 0.15 mm diameter gives the lowest surface roughness of 1.957 µm.
- Both the small size wire electrode of 0.15mm and 0.20 mm gives best MRR values of 2.24 mm^3/min(Experiment run :8)and 3.49 mm^3/min(Experiment run:17) respectively while cutting Inconle718 of 12 mm thickness workpiece.

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